A New Mechanism of Neutrino Mass Generation and Associated Higgs Signals

Steven Gabriel

In collaboration with S. Nandi

Higgs Overview

•Responsible for breaking of electroweak gauge symmetry
→ Gives mass to SM particles

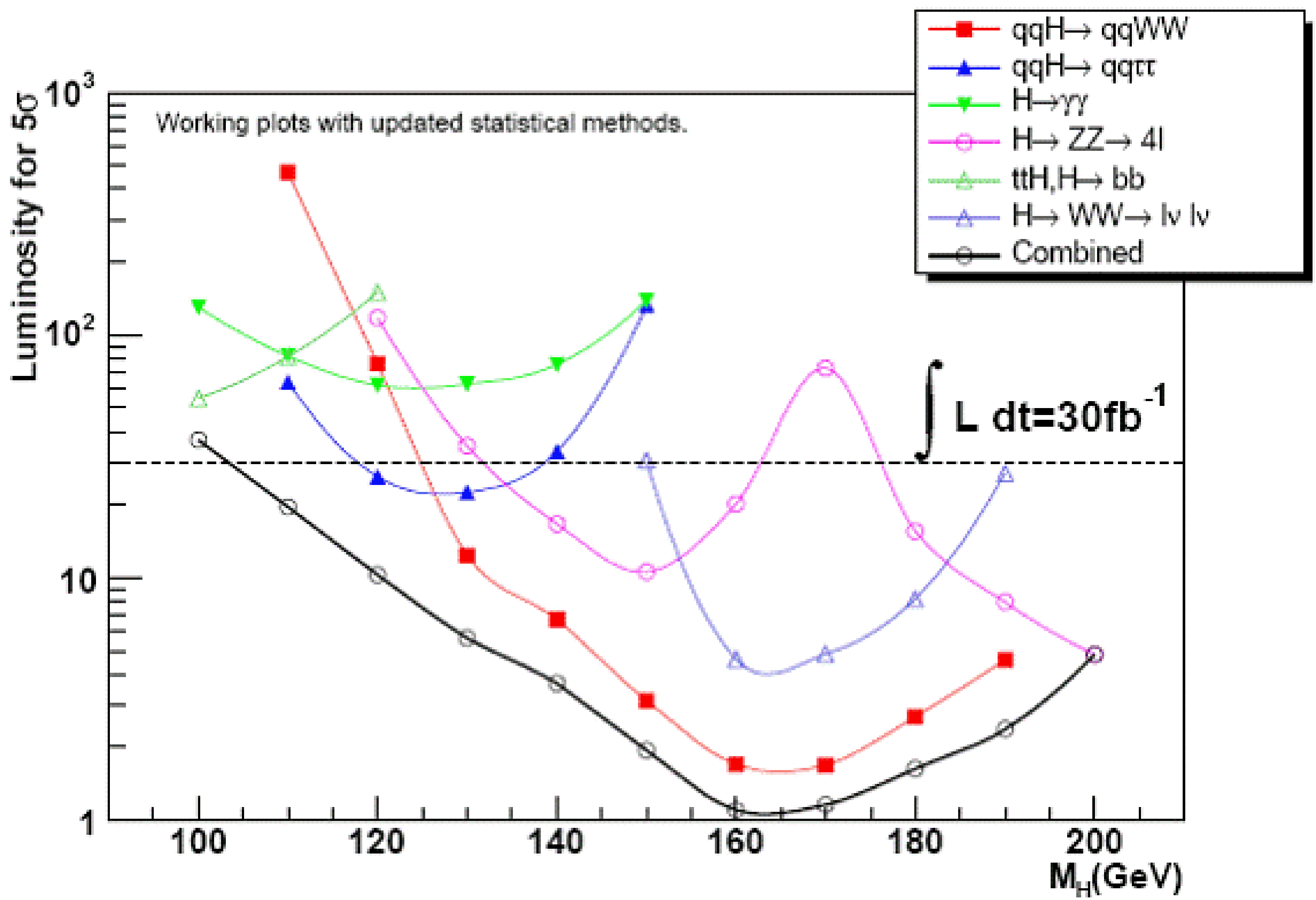
•Mass bound: $m_h > 114.4$ GeV (LEP)

•Dominant decay modes:

$$b\bar{b},\ WW,\ ZZ,\ t\bar{t}$$

depending on the mass

•Experimentally, nothing currently known about Higgs sector



qqH→ qqWW
qqH→ qqττ
H→γγ
H→ ZZ→ 4l
ttH,H→ bb
H→ WW→ lν lν
Combined
Working plots with updated statistical methods.
∫ L dt=30fb⁻¹
Luminosity for 5σ
M_H(GeV)
1
10
10²
10³
100
120
140
160
180
200

Two Higgs Doublet Models

- One doublet gives mass to up-type fermions only, the other to down-type fermions only. Motivated by SUSY

- Only one doublet couples to fermions, but both have VEV

- Only one doublet couples to fermions, and only that doublet has VEV. Motivation: Heavy Higgs, Higgs dark matter (Barbieri, Hall, and Rychkov)

Our Model

- One doublet gives mass to all SM fermions except neutrinos

- Other doublet gives mass only to neutrinos

- Gives an alternative explanation of small neutrino masses

• Symmetry SM×Z_2

•Right-handed neutrinos N_R and two Higgs doublets χ, φ

•SM fermions, χ even under Z_2

•N_R, φ odd under Z_2

•$\langle \chi \rangle \simeq 250\,GeV, \quad \langle \phi \rangle \sim 10^{-2} - 1\,eV$

•Lepton Yukawa interactions:

$$y_l \overline{\Psi}^l{}_L\, l_R \chi + y_{\nu_l} \overline{\Psi}^l{}_L\, N_R \tilde{\phi} + h.c., \quad \overline{\Psi}^l{}_L = (\bar{\nu}_l, \bar{l})_L$$

→ Neutrinos get tiny mass from breaking of Z_2 symmetry

•Neutrinos are Dirac particles

→ No neutrino-less double beta decay

Higgs Potential:

$$V = -\mu_1{}^2 \chi^\dagger \chi - \mu_2{}^2 \phi^\dagger \phi + \lambda_1 (\chi^\dagger \chi)^2 + \lambda_2 (\phi^\dagger \phi)^2$$

$$+\lambda_3 (\chi^\dagger \chi)(\phi^\dagger \phi) - \lambda_4 \left|\chi^\dagger \phi\right|^2 - \tfrac{1}{2} \lambda_5 \left[\left(\chi^\dagger \phi\right)^2 + \left(\phi^\dagger \chi\right)^2 \right]$$

Physical Higgs Particles:

- Charged Higgs $H^{+/-}$
- Neutral pseudoscalar ρ
- Two neutral scalars h, σ

In Unitary Gauge:

$$\chi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\,\frac{V_\phi}{V} H^+ \\ h_0 + i\frac{V_\phi}{V}\rho + V_\chi \end{pmatrix}$$

$$V^2 = V_\chi^{\ 2} + V_\phi^{\ 2}$$

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} -\sqrt{2}\,\frac{V_\chi}{V} H^+ \\ \sigma_0 - i\frac{V_\chi}{V}\rho + V_\phi \end{pmatrix}$$

Higgs Masses:

$$m_H{}^2 = \tfrac{1}{2}\left(\lambda_4 + \lambda_5\right)V^2, \quad m_\rho{}^2 = \lambda_5 V^2$$

$$m_{h,\sigma}{}^2 = \left(\lambda_1 V_\chi{}^2 + \lambda_2 V_\phi{}^2\right)$$

$$\pm\sqrt{\left(\lambda_1 V_\chi{}^2 - \lambda_2 V_\phi{}^2\right)^2 + \left(\lambda_3 - \lambda_4 - \lambda_5\right) V_\chi{}^2 V_\phi{}^2}$$

→ very light scalar: $m_\sigma{}^2 = 2\lambda_2 V_\phi{}^2 + O\left(V_\phi{}^2 / V_\chi{}^2\right)$

$$m_h{}^2 = 2\lambda_1 V_\chi{}^2 + O\left(V_\phi{}^2 / V_\chi{}^2\right)$$

Mass Eigenstates h, σ:

$$h_0 = ch + s\sigma , \quad \sigma_0 = -sh + c\sigma$$

$$c = 1 + O(V_\phi^{\ 2} / V_\chi^{\ 2}), \quad s = -\frac{\lambda_3 - \lambda_4 - \lambda_5}{2\lambda_1}(V_\phi / V_\chi) + O(V_\phi^{\ 2} / V_\chi^{\ 2})$$

→ Mixing is very small

Note: h behaves essentially like the SM Higgs in interactions with fermions and gauge bosons

Phenomenological Implications

Light scalar σ

Possible decay modes:

- $\sigma \to \nu\bar{\nu}, \quad if \quad m_\sigma > 2m_\nu$
- $\sigma \to \gamma\gamma \quad (one\ loop)$

$$\Gamma \sim \frac{e^8 m_\sigma{}^5}{m_q{}^4} \quad \Rightarrow \quad \tau \sim 10^{20}\, yrs$$

→ σ only observable at colliders as missing energy

Couplings of σ to quarks and charged leptons are highly suppressed

ZZσ coupling is proportional to V_Φ

$$\Rightarrow \quad e^+e^- \to Z^* \to Z\sigma, \quad Z \to Z^*\sigma \to f\bar{f}\sigma$$

are suppressed by a factor of $(V_\Phi/m_Z)^2$

However, ZZσσ coupling is unsuppressed:

$$Z \to Z^*\sigma\sigma \to f\bar{f}\sigma\sigma$$

$$\sum_f \Gamma(Z \to f\bar{f}\sigma\sigma) \simeq 2.5\times10^{-7}\,GeV$$

Total Z width = 2.4952 +/- 0.0023 GeV (PDG)

At LEP1, ≈ 1.7×10^7 Z's → ≈ 2 such events

Coupling of σ to neutrinos is relatively large

$\Rightarrow \quad Z \rightarrow \nu \overline{\nu} \sigma$ can be significant

$$\Gamma(Z \rightarrow \nu \overline{\nu} \sigma) \simeq (2.5\, MeV)\, y_{\nu}^{2}$$

$$\Rightarrow \sum y_{\nu}^{2} < 0.6$$

Invisible Z width = 499 +/- 1.5 MeV (PDG)

Can also have $\pi \rightarrow \mu \nu \sigma$

$$B(\pi \rightarrow \mu \nu \sigma) \simeq 0.05\, y_{\nu}^{2}$$

$$\Rightarrow y_{\nu} < 0.2$$

Pseudoscalar ρ

No strong coupling

$\rightarrow \quad \frac{\lambda_5}{4\pi^2} \leq 1 \quad \Rightarrow \quad m_\rho \leq 470\ GeV$

$$Z \rightarrow \rho\sigma, \quad Z \rightarrow \rho^*\sigma \rightarrow \nu\bar{\nu}\sigma$$

Note: Couplings of ρ to quarks and charged leptons are VEV suppressed

→ For $m_\rho < m_Z, \quad \rho \rightarrow \nu\bar{\nu}$ dominant decay mode

$\Rightarrow \quad Z \rightarrow \rho\sigma$ invisible

Invisible Z width = 499 +/- 1.5 MeV (PDG)

$$\Gamma(Z \to \rho\sigma) = \frac{G_F m_Z^{\ 3}}{24\sqrt{2}\pi}\left(1 - \frac{m_\rho^{\ 2}}{m_Z^{\ 2}}\right)^3 < 1.5\ MeV$$

For m_ρ > 78 GeV

For m_ρ > m_Z, we have $e^+e^- \to Z^* \to \rho\sigma$

$$\sigma = \frac{G_F m_Z^{\ 4}(g_V^{\ 2} + g_A^{\ 2})s}{24\pi}\left(\frac{1}{s - m_Z^{\ 2}}\right)^2\left(1 - \frac{m_\rho^{\ 2}}{s}\right)^3$$

At LEP2, with √s ~ 200 GeV and ~ 3000 pb^{-1} of data, < 1 event is expected for m_ρ > 95 GeV

Heavy scalar h

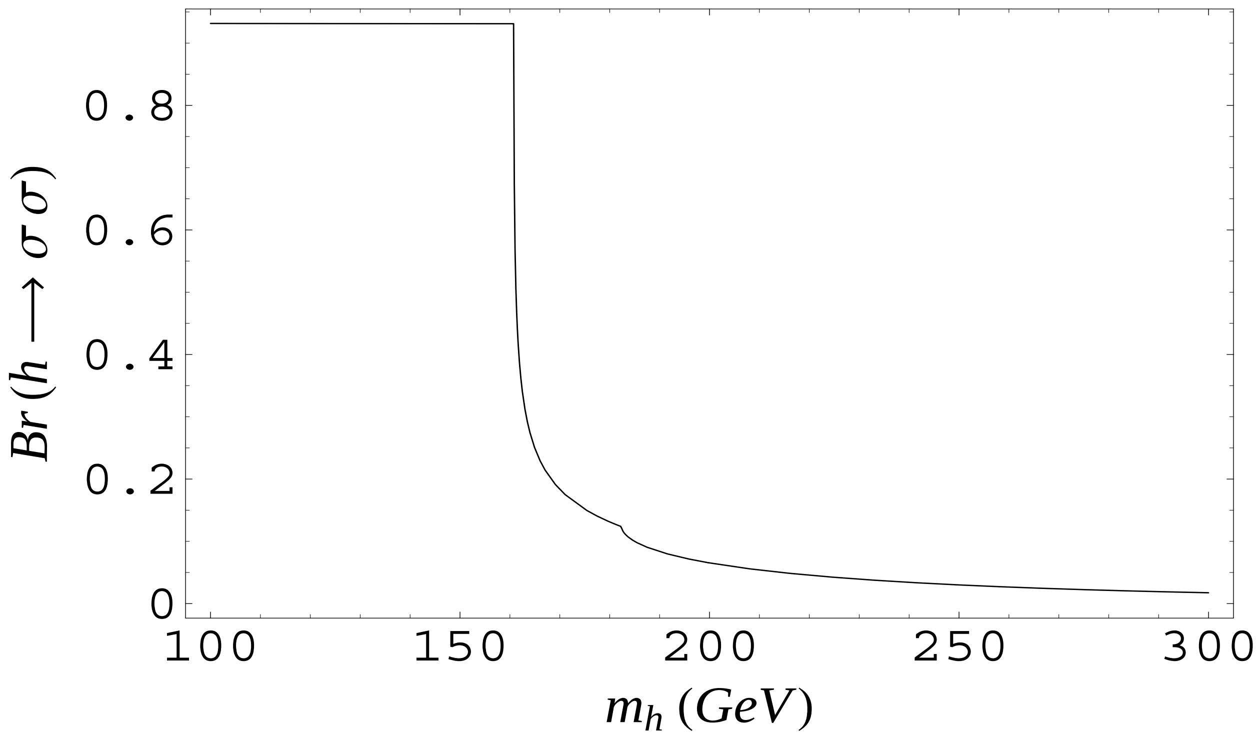
Essentially SM Higgs

Invisible decay mode: $h \rightarrow \sigma\,\sigma$

$$\Gamma(h \rightarrow \sigma\sigma) = \frac{(\lambda_3 + \lambda_4 + \lambda_5)^2 V_\chi^{\ 2}}{32\pi m_h}$$

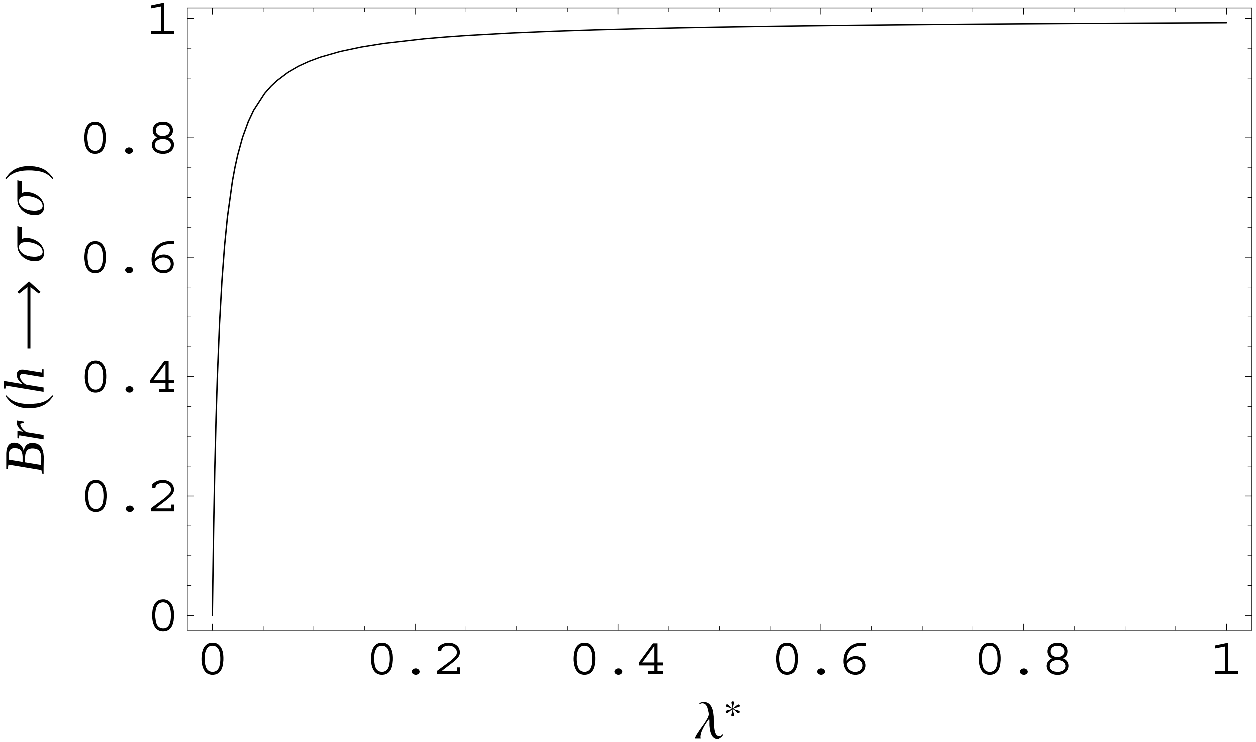
$$m_h^{\ 2} = 2\lambda_1 V_\chi^{\ 2} + O(V_\phi^{\ 2} / V_\chi^{\ 2})$$

$$\Gamma(h \rightarrow \sigma\sigma) = \frac{(\lambda_3 + \lambda_4 + \lambda_5)^2 m_h}{64\pi\lambda_1} \equiv \frac{\lambda^* m_h}{64\pi}$$



0.8
0.6
0.4
0.2
0
100
150
200
250
300
$Br(h \longrightarrow \sigma\sigma)$
$m_h\,(GeV)$

$\lambda^* = 0.1$



$m_h = 135\, GeV$

For a wide range of λ^*, this mode dominant for m_h < 160 GeV

Current limit for invisible Higgs: m_h > 112.3 GeV (L3)

At LHC, invisibly decaying Higgs observable through WBF:

$$qq \to qqWW \to qqh, \quad qq \to qqZZ \to qqh$$

Signal: Two q's with high p_T + invisible

This signal can be observed at 95% CL with >10 fb^{-1} of data if B($h \to$invisible) > 30% and m_h < 400 GeV (Eboli and Zeppenfeld)

Difficult to identify invisible particle as Higgs

Cosmological Implications

Big-Bang Nucleosynthesis

•Predicted light element abundances depend on the number g_* of light spin degrees of freedom in thermal equilibrium at T ~ 1 MeV

$$g_* = g_b + \tfrac{7}{8} g_f$$

•In the standard scenario (SBBN), this includes γ, $e^{+/-}$, ν_L's:

$$(g_*)_{SBBN} = 2 + \tfrac{7}{8}(4) + \tfrac{7}{8}(6) = 10.75$$

•In our model, relatively strong interactions between left- and right-handed neutrinos and the light scalar σ will keep them in thermal equilibrium

$$g_* = (g_*)_{SBBN} + 1 + \tfrac{7}{8}(6) = 17$$

$$N_{eff} = 6 + \tfrac{4}{7}$$

•Reactions that interconvert protons and neutrons fall out of thermal equilibrium at a higher temperature ($T \sim g_*^{1/6}$)

•Leads to larger ratio of neutrons to protons during BBN

•Gives a mass fraction of He-4 produced during BBN of $Y_P \approx 0.30$

•Observed value: $Y_P \approx 0.25$

Possible Solution: Large Neutrino Degeneracy

•SBBN assumes $\mu_\nu \approx 0$, but it has not been measured directly

•Alters equilibrium value of neutron to proton ratio to

$$\frac{n}{p} = e^{-\frac{\mu_\nu}{T}} \left(\frac{n}{p} \right)_{\mu_\nu = 0}$$

•We require μ_ν/T to be order 0.1

•Studies that allow μ_ν/T, N_{eff}, and Ω_B to vary within observational constraints from BBN+WMAP find an upper bound on N_{eff} from 7.1 to 8.7 (Barger *et al.*, 2003; Cuoco *et al*., 2004, Steigman, 2005)

Another Possible Solution: Late-Decaying Particles

•The energetic decay products of a massive particle (m > a few GeV) that decays during or after nucleosynthesis can cause nuclear reactions among background nuclei, altering light element abundances

Non-BBN Bounds on Number of Neutrinos

•WMAP+LRG's: $0.8 < N_{eff} < 7.6$ (Ichikawa, Kawasaki, Takahashi, Nov. 2006)
•Seljak, Sloshar, McDonald (WMAP + several other astrophysical data sources) claim that more than 3 neutrinos is required (Sep. 2006)

Domain Walls

•Breaking of discrete Z_2 symmetry will lead to cosmological domain walls

•Energy per unit area: $\eta \sim V_\varphi^3$

→Produces temperature anisotropies:

$$\frac{\delta T}{T} \simeq G \eta H_0^{-1} \sim 10^{-20}$$

•Observed level of temperature anisotropies is 10^{-5}

Conclusions

- Proposed new two Higgs doublet model based on SM×Z_2
- Z_2 broken at ~ 10^{-2} eV
- Gives new mechanism for tiny neutrino mass
- Neutrinos are Dirac particles
- Higgs: $H^{+/-}$, h, ρ $\rightarrow$ mass at EW scale, $\sigma \rightarrow$ extremely light
- h like SM, but possibly dominant invisible decay mode h $\rightarrow \sigma\sigma$
- Alters Higgs signals at LHC, but observable through WBF
- BBN problem solvable